

Jet reconstruction in heavy ion collisions

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Abstract. The STAR experiment at RHIC detects Au+Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$. The very short lived (\sim few fm/c) and highly dense medium created in these collisions has been probed with hadrons of high transverse momentum. Di-hadron azimuthal correlations and nuclear modification factor measurements have been used in the past to probe the medium. These measurements have known geometrical bias and limited kinematic reach. One way to improve on these limitations and get more insight into jet modification is to recover the hard scattered partons kinematics by jet reconstruction which supports the interesting possibility of transverse momentum redistribution with minimal energy loss. The k_T and anti- k_T jet finding algorithms are being used for jet reconstruction in STAR. One of the most significant challenges for jet reconstruction in the heavy ion environment comes from the correct characterization of the significant background fluctuations. The background is being subtracted by assigning areas to the jets and calculating per event background densities. The jet momentum irresolution due to background fluctuations has to be understood in order to recover the correct jet spectrum. Recent progress in jet reconstruction measurements and methodology in heavy ion collisions at STAR will be presented.

1. Heavy ion collisions' prior probes

Relativistic heavy ion collisions have been extensively studied via un-triggered particle correlations in $(\Delta\eta, \Delta\phi)$ (all particles with transverse momentum (p_T) above 150 MeV/c are accepted). STAR has measured the per final state particle 2D correlations at $\sqrt{s_{NN}} = 200, 62 \text{ GeV}$ Au+Au peripheral to central collisions [1]. The correlation signal can be fit by a function composed of a constant offset, a dipole and a quadruple in $\Delta\phi$, a $\Delta\phi$ independent Gaussian, and a 2D Gaussian [1]. The 2D Gaussian centered at $\Delta\eta, \Delta\phi$ can be attributed to minijets [1][2][3]. It is observed that the amplitude and $\Delta\eta$ width of the Gaussian increases with collision centrality deviating from Glauber linear superposition [1]. The width on the $\Delta\phi$ variable has a small decrease in the most peripheral bins and stays constant as we move from mid central to central events. A jet signal structure survives even at the highest centrality in $\sqrt{s_{NN}} = 200 \text{ GeV}$ Au+Au events.

The transient character of the medium created in Heavy Ion Collisions (HIC) (lasting \sim few fm/c) pushes physicists to look for probes created in the collisions themselves. Jets coming from hard scatterings constitute such probe. Distinguishing single jets in the HIC environment is challenging, therefore, high p_T particles are used as jets proxies. The correlations in $\Delta\phi$ of high p_T particles relative to different p_T associated particles are studied. STAR measurements have established the suppression of high p_T particles (3-6 GeV/c) recoiling from higher p_T trigger hadrons (8-15 GeV/c) in central $\sqrt{s_{NN}} = 200 \text{ GeV}$ Au+Au collisions [5]. Similarly, and enhancement of low p_T (0.5-4 GeV/c) multiplicity and p_T sum is found in the recoiling side of a trigger ($p_T = 4-10 \text{ GeV/c}$) [4]. A

possible explanation of these observations is the softening of jet fragments. High p_T hadron triggers have a surface bias. We preferentially select jets that have interacted the least with the medium. This bias can be used to study path length dependence of jet quenching (looking at the recoil side) but is undesirable if the goal is to measure the inclusive jet p_T spectrum. A surface bias free measurement can be obtained via gamma-jets. The small mean free path of a direct gamma traversing the medium assures that it conveys its recoiling parton kinematics. The downside of this otherwise golden probe is its limited statistics at RHIC energies. An additional approach free of surface bias and with higher statistics is to perform full jet reconstruction.

2. Jet finding algorithms used at STAR

There are several jet finding algorithms in the literature (cone algorithms, sequential recombination, Gaussian filtering). A desirable characteristic of a jet finding algorithm (JFA) is that it would be infrared and collinear safe. This allows for meaningful comparison with pQCD calculations. The k_T and anti- k_T JFA from the FASTJET package are being used at STAR [6][7][8][9]. This package includes a jet area calculation which is very useful for background estimation in heavy ion collision events [8]. A jet area is related to the likelihood of a jet to cluster background particles. It is the number of infinitesimal transverse momentum particles that would get clustered in a jet that is embedded in a dense event containing those particles. The input of any JFA is a set of particles to be clustered. STAR can combine charged hadron measurements with neutral particles due to its Time Projection Chamber (TPC) and Barrel Electromagnetic Calorimeter (BEMC). The TPC is embedded on a 0.5 Tesla magnetic field for transverse momentum determination. It can measure charged tracks of p_T from 150 MeV/c up to ~ 15 GeV/c before the p_T determination becomes prohibitive. It has a pseudorapidity coverage of $|\eta| \leq 1.8$ [10]. The Barrel Electromagnetic Calorimeter (BEMC) consist of 4800 towers with granularity of 0.05×0.05 in $\delta\eta, \delta\phi$ size [11]. Gammas and π^0 decays are detected at the BEMC. STAR does not have K_L^0 nor neutron detection capabilities. Both TPC and BEMC have full azimuth coverage. The wide STAR detector acceptance makes it an excellent detector for jet reconstruction.

3. Preliminary jet measurements in central Au+Au Collisions at RHIC

Jets produced in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV at STAR are well described by pQCD up to jet p_T of 50 GeV [12]. The inclusive jet cross section was obtained with a midpoint cone algorithm with a radius = 0.4. A new measurement of the jet cross section in p+p was made with the anti- k_T and k_T JFAs and a $R = 0.4$ resolution parameter. The measurement with the two different JFAs is consistent with the published cross section and with pQCD calculations. We conclude that jets are a well calibrated probe to study any effects of the medium on them; furthermore, the choice of JFA does not affect the jets spectrum measurement in p+p collisions. Jet reconstruction gets more challenging in HICs.

A single central Au+Au collision at RHIC energies produces of the order of 5k particles with $\langle p_T \rangle \sim 0.5$ GeV/c. Jets have to be reconstructed on top of this background. A given JFA cannot distinguish between particles coming from the fragmentation of a single hard scattered parton and any other particles present in a heavy ion collision on a jet by jet basis. The JFA recombination scheme chosen for these studies returns a 4 vector sum from the hadrons that fragmented from the hard scattered parton and possibly emitted gluons if the parton interacts with other colored objects. But that is not the end of the story; other hadrons in the vicinity of the jet-related particles get clustered to build the final jet as well. These "background" hadrons can come from another hard scattering, soft scattering, or elastic collision that just happen to overlap in $\eta - \phi$ space. The fundamental assumption in jet reconstruction studies in HIC is that the contribution of this background and the contribution coming from the jet can be factorized. We have chosen to use a jet-area based background correction scheme [8][9]. All particles in the event get clustered and the output clusters are all initially considered to be jets. A given event background is estimated by measuring the ratio

of the jets's transverse momentum ($P_T^{cluster}$) over its area (A_{jet}), and extracting the median (ρ) of that ratio from the ensemble given by all the jets in the event. The expected background of any given jet is then ρA_{jet} and its measured transverse momentum: $P_T^{measured} = P_T^{cluster} - \rho A_{jet}$. Unfortunately, the event background is not uniform. These background fluctuations give irresolution in $P_T^{measured}$. The steeply falling P_T cross section of high transverse momentum jets at $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions is severely affected by this irresolution which smears the measured spectrum. A p_T cut in the particles used for jet reconstruction in Au+Au collisions can be applied to reduce the background contamination of the p_T of the jet. This comes at the expense of possibly biasing your reconstructed jet signal towards jets that do not interact with the medium. It has been found that background fluctuations increase with the jet area (~ 6 GeV/c for $R = 0.4$ at 0 – 20% most central Au+Au collisions) [13]. A small resolution parameter is therefore desired with the caveat that you might miss more of the jet's energy in the presence of gluon radiation at angles bigger than the jet area. The bias and interplays of a p_T cut and resolution parameter in jet reconstruction can be used to test jet-medium modification scenarios [14][15].

The P_T^{jet} spectra of background corrected jets in Au+Au collisions has been measured at STAR via deconvolution(unfolding) of the background fluctuations which were initially assumed to have a Gaussian distribution. All particles in an event get clustered by the JFA. Some of those clusters of particles could lie on a region of the event with an upward background fluctuation and end up mocking a real high p_T jet. Uncorrelated clusters of particles that contribute to the jet spectrum signal are called fake jets (uncorrelated in the sense of belonging to a single parton fragmentation, this cluster could have correlations among its constituents particles). The spectrum is corrected from fake jets contamination by subtracting the yield produced by running the JFA on central Au+Au events that had their particles randomized in azimuth. This effectively destroys any previous correlations and other less "destructive" schemes of fake jet estimations are under study.

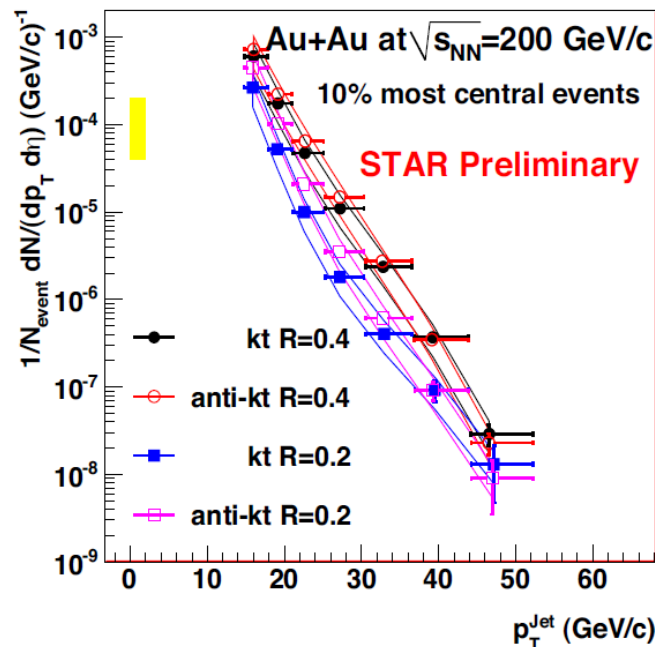


Figure 1. Inclusive jet p_T spectrum in 10% most central $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions. k_T and anti- k_T JFA were used along with resolution parameters of $R = 0.4$ and $R = 0.2$. The yellow band is the jet energy scale uncertainty and the solid lines represent the systematic uncertainty due to event background fluctuations

STAR has preliminary results on the jets nuclear modification factor R_{AA} at 10% most central $\sqrt{s_{NN}} = 200 \text{ GeV}$ Au+Au collisions [16]. R_{AA} has been measured with two distinct JFA (k_T and anti- k_T) and two resolution parameters ($R=0.2$, $R=0.4$). The nuclear modification factor of jets is consistent with one (Nbin scaling of jets production in Au+Au) for $R = 0.4$ but it is smaller than one for $R = 0.2$. This is a sign that not all jets are recovered since they should scale with the number of binary collisions due to their hard scattering origin. A decrease of R_{AA} for smaller resolution R is to be expected since in the limit of $R \rightarrow 0$ we would recover the single hadron suppression $R_{AA} = 0.2$. In order to test if the smaller R_{AA} in $R=0.2$ compared to $R=0.4$ is due to jet broadening, the ratio or spectra with the two resolution parameters was measured both in p+p and (0-10%) central Au +Au collisions at the same per nucleon pair center of mass energy. The jet yield ratio in the p+p system is smaller than zero and increases with jet's p_T . This result is consistent with vacuum Q-PYTHIA and PYTHIA + underlying event simulations. The increasing ratio with p_T of the jet can be explained as a manifestation of the jet collimation with increasing energy measured in other experiments [17][18]. The yield ratio in Au+Au is suppressed. This is suggestive of a broadening of the jets in Au+Au collisions.

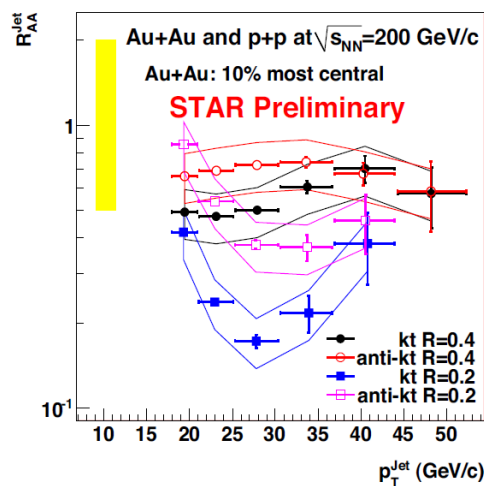


Figure 2. Nuclear modification factor in $\sqrt{s_{NN}} = 200 \text{ GeV}$ Au+Au collisions using two different JFA and two different resolution parameters. A clear suppression for $R = 0.2$ is seen.

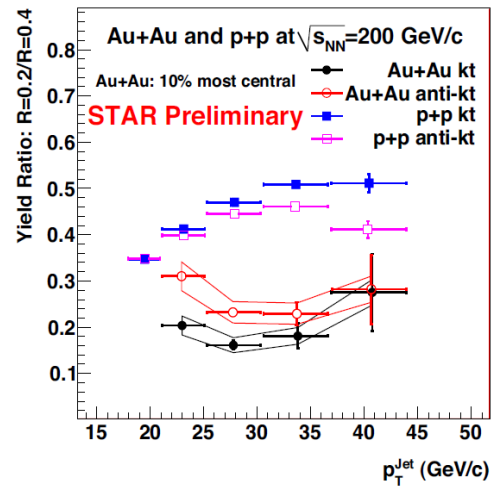


Figure 3. Yield ratio ($R = 0.2$)/($R = 0.4$) of jet p_T spectra in $\sqrt{s_{NN}} = 200 \text{ GeV}$ p+p collisions (blue and magenta) and in $\sqrt{s_{NN}} = 200 \text{ GeV}$ Au+Au collisions (black and red). The Au+Au ratio gets suppressed.

One way to test that jets do get broaden is via jet+hadron correlations [19]. A reconstructed high p_T jet ($P_T^{jet} > 20 \text{ GeV/c}$) is correlated with softer ($0.2 \leq p_T \leq 1.0 \text{ GeV/c}$) associated particles. Triggering on a jet has the advantage of accessing higher kinematics and a clearer distinction of the correlation measure above background as compared to high p_T hadron trigger correlations. The associated particle multiplicity in the direction of the jet ($\Delta\phi \sim 0$) and recoiling from the jet ($\Delta\phi \sim \pi$) increases in Au+Au collisions compared the the p+p reference. There is also a broadening in the correlation width more obvious in the recoiling side. Increasing the p_T of the associated particles to 1 - 2.5 GeV/c results in an enhancement of the correlation amplitude on the jet direction's side and reduction in the away side amplitude (so that now it matches the amplitude in the away side in p+p collisions). The broadening on the away side correlation signal persists. These results are consistent with a broadening of the jet due to radiation of energy of the original parton.

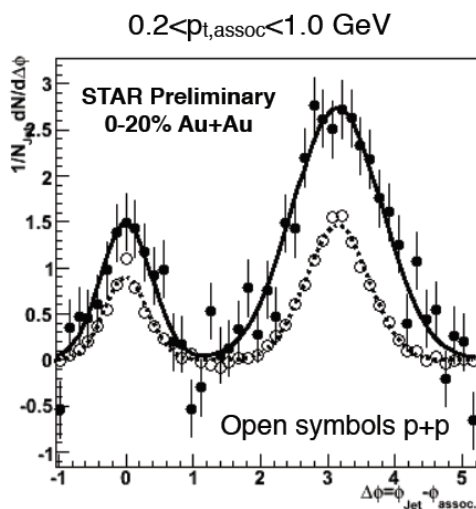


Figure 4. Jet-hadron correlation on $\Delta\phi$ for a triggered jet of $P_T^{jet} > 20 \text{ GeV}/c$ and associated hadrons of $0.2 < p_t^{assoc} < 1.0 \text{ GeV}/c$ for central Au+Au collisions (filled circles) and p+p collisions (hollow circles) at $\sqrt{S_{NN}} = 200 \text{ GeV}$

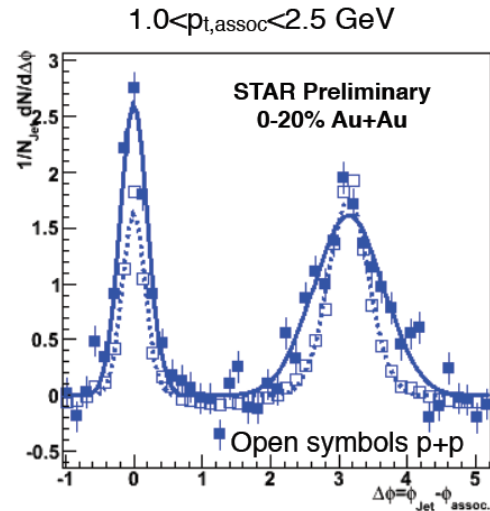


Figure 5. Jet-hadron correlation on $\Delta\phi$ for a triggered jet of $P_T^{jet} > 20 \text{ GeV}/c$ and associated hadrons of $1.0 < p_t^{assoc} < 2.5 \text{ GeV}/c$ for central Au+Au collisions (filled squares) and p+p collisions (hollow squares) at $\sqrt{S_{NN}} = 200 \text{ GeV}$

4. Recent background fluctuation studies

Much progress has been made in the study of the underlying HIC event background since the preliminary results on the jet spectra were first presented [16] [20]. The $P_T^{measured}$ irresolution can be quantified by embedding a known probe in a central event and measuring the excess (or deficit) of transverse momentum after background subtraction. The background fluctuation (jet irresolution) is therefore defined as: $\delta P_T = P_T^{cluster} - \rho A_{jet} - P_T^{embed}$. Where ρ is calculated before the probe is embedded. We measure the probability of fluctuations δP_T by embedding different P_T^{embed} probes in several central Au+Au events. This probability is the response of a given signal to the heavy ion background. We find that the probability of fluctuations depends trivially on the area of the jet and also on its initial transverse momentum, but it does not depend strongly on the initial jet fragmentation pattern [20]. The measured jet spectrum is a convolution of the probability of fluctuations with the inclusive jet spectrum. The inclusive jet spectrum is what we would like to recover via deconvolution. It is worthwhile to notice that a simple statistical distribution describes the background fluctuations of jets reconstructed with random cones ($R = 0.2$), and the fast-jet anti k_T algorithm on a simulated thermal background with particles randomly localized in $\eta - \phi$ space.

5. Jet Shapes Background

Jet shapes have been measured in $p - \bar{p}$ collisions at $\sqrt{S} = 1.96 \text{ TeV}$, in $p - e^+$ DIS at $\sqrt{S} = 300 \text{ GeV}$ and in $p - p$ collisions at $\sqrt{S} = 200 \text{ GeV}$ [17][21][22].

The following analysis is not concerned with the jet spectrum measurement itself but with the characterization of the fluctuations in the jets' differential shape measurement. The differential jet shape (DJS) is the rate of change of a jet's transverse momentum with distance in $\eta - \phi$ space from the jet axis normalized by the total jet's P_T . This definition only makes sense in practice as an average over many jets at the same P_T^{jet} . We have to measure the amount of P_T at a distance r for each jet. The JFA response to the HIC background can have the following effects on the DJS. It could change the measured jets total transverse momentum. It could change the measured transverse

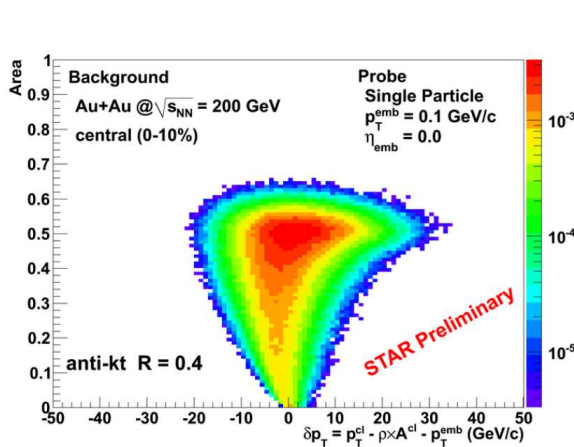


Figure 6. δP_T and A_{jet} distribution for a single particle $P_T^{embed} = 0.1 \text{ GeV}/c$ embedded in $\sim 8\text{M}$ 0-10% most central $\sqrt{s_{NN}} = 200 \text{ GeV}$ Au+Au events. An anti- k_T with a resolution parameter of $R = 0.4$ JFA was used.

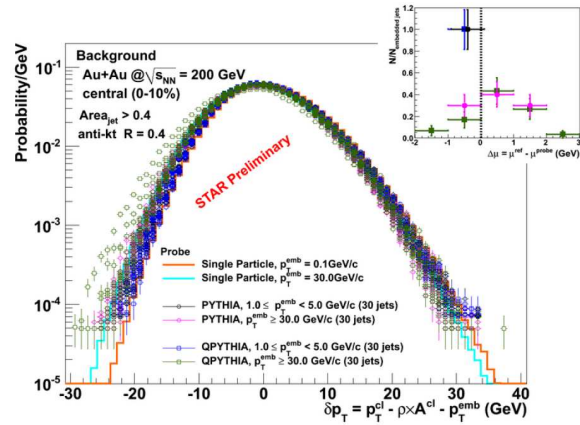


Figure 7. δP_T distribution for different P_T^{jet} embedded jets. Up to 30 different jets produced with PYTHIA and Q-PYTHIA were embedded. All the distributions are similar to within a factor of two, showing the independence of the distributions on the fragmentation pattern of the jets.

momentum at a distance r from the jet axis and it might change the original jet axis. The measured (background subtracted) jet shape will have a probability of fluctuations that we have to take into account in order to get the differential jet shape signal.

Following the jet area based background subtraction method we calculate the area of concentric rings of width $\delta r = 0.1$ and multiply it by ρ to estimate the amount of background at a given distance from the jet axis. The total transverse momentum of the jet is still corrected using its total area. A point of warning is that this method will only probe the jets internal momentum distribution up to a distance smaller than your R parameter, missing the region where very interesting phenomena are encountered (i.e. $\Delta\eta$ ridge).

It has been found that the background fluctuations grow with area [13]. Therefore, we expect smaller fluctuations in the shape measurement closer to the jet axis (smaller ring) but those fluctuations are correlated with the total δP_T of the jet. The measured DJS at a distance r is:

$$\frac{1}{N_{jet}} \sum_{jets} \frac{1}{\delta r} \frac{P_T^{jet}(r) - 2\pi r \rho \delta r}{P_T^{jet} - \rho A_{jet}} \quad (1)$$

The probability of fluctuations is obtained by embedding a probe with known differential jet shape signal (a single high p_T pion, whose jet shape is zero at any distance r) and subtracting that signal after having applied the background subtraction. The obtained distribution is normalized to one. For the case of a single pion the fluctuation is

$$\delta\psi(r) = \frac{1}{\delta r} \frac{p_T^{cluster}(r) - 2\pi r \rho \delta r}{p_T^{cluster} - \rho A_{jet}} \quad (2)$$

We embedded a single $p_T = 30 \text{ GeV}/c$ pion at $\eta = \phi = 0$ in $\sim 150\text{k}$ central Au+Au events at $\sqrt{s_{NN}} = 200 \text{ GeV}$ from Run 2007 in order to extract the probability of fluctuation of the DJS as a function of distance from the jet axis (r). We reconstruct the jet containing the embedded pion with the anti- k_T JFA using a resolution parameter $R = 0.6$. We calculated the background

using the k_T JFA with the same resolution parameter. The k_T algorithm is preferred to the anti- k_T algorithm as a ρ estimator due to the tendency of clustering jets of very small areas of the later. The presented probability of fluctuations is for charged particles only and the background at a given ring was calculated with charged particles accordingly.

Both charged and neutral particles are used to obtain the total jet transverse momentum. An area cut was imposed in the studied jets in order to avoid a trivial edge deficit problem. Only jets with area, $\pi R^2 \leq A_{jet} \leq \pi R^2 + 0.05$, were accepted. Only particles with $p_T > 0.2$ GeV/c were used. An $|\eta| < 1 - R$ cut was imposed on jets to assure that the complete jet area is within the detector acceptance. The central Au+Au events to embed the pion were chosen to have a z vertex cut of < 30 cm and reference multiplicity > 400 . The transverse momentum of charged particles matching a signal from a calorimeter tower is subtracted to avoid double counting. The probability of fluctuations show the expected area dependence being wider for bigger r (i.e. bigger ring area). A value of zero $\delta\psi$ means that we have accomplished perfect background subtraction. We have chosen an r bin size of 0.1. Expected typical values of $\psi(r)$ at the considered jet energy vary between 0-10 [23]. Therefore a fluctuation of 1 can represent a change in the DJS 10% or more. The probability of fluctuations for a relative distance of $r/R = 0.249$ has 93.5% (74.6 %) of its distribution in the $\delta\psi(r/R)$ interval of $[-1, 1]$ $[-0.5, 0.5]$. This indicates that there is a $\sim 25\%$ of probability that the jet shape measurement after background subtraction is off by an amount bigger than 0.5. The probability of fluctuations for a relative distance from the jet axis of $r/R = 0.849$ has 74.2% (46.3 %) of its distribution in the $\delta\psi(r/R)$ interval of $[-1, 1]$ $[-0.5, 0.5]$. The probability of fluctuations of the DJS for a 30 GeV/c jet are narrow enough that we can attempt a deconvolution of the measured signal in central Au+Au collisions.

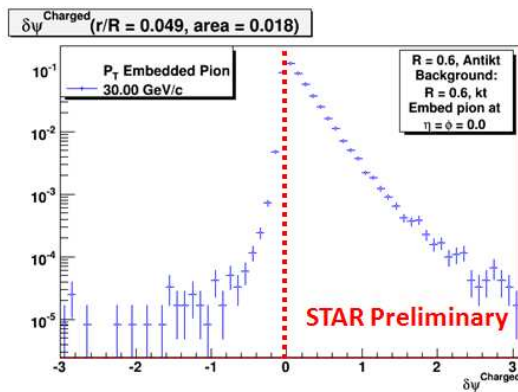


Figure 8. δr probability distribution for a $P_T = 30$ GeV/c embedded pion at a relative distance from the jet axis of $r/R = 0.049$. Jet reconstruction was done with anti- k_T (k_T for background determination), $R = 0.6$ JFA. The ring area is 0.018.

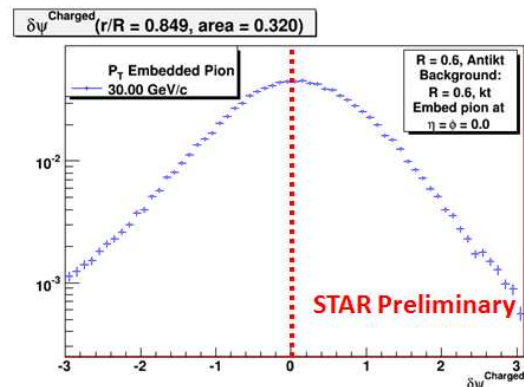


Figure 9. δr probability distribution for a $P_T = 30$ GeV/c embedded pion at a relative distance from the jet axis of $r/R = 0.849$. The ring area is 0.320. The fluctuations in the DJS are wider for a greater area as expected.

6. Conclusions

Jets are a calibrated probe that can be used to expand current studies of the medium created in HIC at RHIC. Preliminary results from jet reconstruction at STAR in $\sqrt{s_{NN}} = 200$ GeV 0-10% most central Au+Au collisions indicate possible jet profile broadening. Jet R_{AA} is found to be consistent with one for resolution parameter $R = 0.4$ but is suppressed at $R = 0.2$. The yield ratio of reconstructed jets with these two parameters show a suppression compared to the same ratio in p+p. This is consistent with a possible broadening of the jets. Jet+hadron correlations confirm

these broadening. Progress has been made on the understanding of the distributions of background fluctuations in central Au+Au events. The distribution of fluctuations of the measured jet transverse momentum is found to be independent of fragmentation patterns. This is important to be able to reconstruct the spectrum in the presence of quenched jets that are expected to have different fragmentation patterns compared to vacuum fragmenting jets. Studies to characterize the effect of background fluctuations for differential jet shapes look promising for Jets of $P_T = 30$ GeV/c.

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